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SYSTEMATIC MEASUREMENTS OF THE BOHR-WEISSKOPF EFFECT AT ISOLDE

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SUMMARY

Extended nuclear electric and magnetic structure properties are measurable by high-resolution atomic spectroscopy through isotope shifts and the Bohr-Weisskopf effect (hyperfine structure anomalies). These add to data obtainable from nuclear moments alone. The greatest value of these measurements is when made systematically over a large number of isotopes. This has been done in the case of isotope shifts most extensively by the experiments at ISOLDE. To date the magnetic distribution studies are few and isolated. Here we propose to initiate a program at ISOLDE to measure hfs anomalies systematically. Recently new importance has been given to nuclear structure knowledge gained in this work by the possible impact on the interpretation of atomic parity nonconservation. The experiments, requiring high-precision data on magnetic dipole constants as well as on nuclear g-factors, will be done by atomic-beam magnetic resonance with the use of laser excitation for polarization of the beam and a sixpole magnet acting as an analyser. The heavy alkali elements are the most promising candidates for hfs anomaly studies because of the large effect expected, the high production yields at ISOLDE and most importantly, the interesting variations in nuclear shape and structure along the isotopic sequences as observed already in the previous hyperfine structure and isotope shift measurements at ISOLDE. We propose to perform the initial hfs anomaly experiments on a selected sequence of cesium isotopes of particular physics importance.

1. Introduction

This is a submission to PSB ISOLDE of a proposal, revised and updated, previously approved (IS190) by SC ISOLDE. It will also report on the progress made in developing the experiments for the eventual on-line work.

The atomic electron produces a magnetic field that is not uniform over the region of the nucleus. The dipole-dipole interaction is thus sensitive to the spatial extent of the nuclear magnetization. This depends on the distribution of spin and orbital moments in the nuclear volume, and therefore differs from isotope to isotope. The hyperfine structure energy is different from that of the hypothetical point nucleus. This difference, known as the Bohr-Weisskopf effect[1], or hfs anomaly, can be used, in turn, to gain knowledge of the effect of the distribution of nuclear magnetization, more specifically the isotopic variations. If one compares this to the electrical structure counterpart measurable by the isotope shifts then the Coulomb interaction between the nuclear and electron charge densities ρ has to be replaced by the corresponding divergences of the magnetizations, $\nabla \cdot M$. The nuclear magnetization information is thus expressible, not as directly as for ρ through essentially the expectation value $\langle R^2 \rangle$ of the charge distribution, but rather through the <u>nuclear wavefunctions</u> with which is tested not only the magnetic moment operator $g_s s + g_l l$, but additionally $[s \times Y^2]^1$, a tensor product of rank 1 of the spin and spherical harmonic of order 2. While this is more indirect, nonetheless in one of the few cases where a short isotopic series has been measured[2], the hfs anomaly for ^{137}Cs appears to display a magic number effect. It is this result which stimulated us[3] to try to account for the Bohr-Weisskopf effect in the light of the shell model with nuclear core polarization, or configuration mixing.[4] Bohr and Reiner treated the hfs anomalies with the collective model.[5] Büttgenbach has reviewed the subject recently.[6] Very few measurements of the hfs anomalies were made systematically in the intervening years because of the difficulties discussed in Sec. II. The status was not unlike isotope shift studies, before the advent of tunable lasers. With the production facilities at ISOLDE, coupled with both laser and atomic beam magnetic resonance techniques, we are now in the position to make systematic measurements of the hfs anomalies. These can be expected to be of value in testing nuclear structure theory.[7] It was also pointed out only very recently[8] that uncertainties in nuclear structure effects, particularly in neutron distributions, can limit the precision of extracting weak interaction parameters from atomic parity-non conservation (PNC) experiments. We have shown[3] how the hfs anomalies, coupled with the magnetic dipole moments, can be used to shed light on the nuclear wave functions. Our experiments comprise the same isotopic sequence as proposed for PNC studies.[9]

The isotopic sequences of the heavy alkali elements rubidium, cesium and francium exhibit interesting structural variations, with spherical nuclei close to the neutron-shell closures at N = 50, 82 and 126, respectively, over transitional to strongly deformed ones far from the shell closures. Information on the nuclear shape and structure along the isotopic chains has been obtained in systematic hyperfine structure (hfs) and isotope shift (IS) measurements performed mainly at the ISOLDE facility. The nuclear single-particle structure and qualitative values of the nuclear deformation were to a large extent determined from the spin and magnetic moment measurements by the atomic-beam magnetic resonance (ABMR) method.[10-15] The results from the laser spectroscopy experiments[16-22], in particular those on spectroscopic quadrupole moments and changes in mean square charge radii, have added quantitative information on the nuclear deformation. The nuclear single-particle structure of the isotopic chains was discussed at the Helsingör Conference[23] and in Ref. 15.

The hfs anomaly, as noted, being the counterpart to the isotope shift measurements, gives additional information on the nuclear single-particle structure by probing the distribution of nuclear magnetization.[1] To determine the hfs anomaly, high-precision measurements are required of both magnetic dipole constants and nuclear g-factors in pairs of isotopes. Hfs anomaly experiments have been performed by the ABMR method in a number of rubidium and cesium isotopes close to the line of beta-stability.[2,24-26] These nuclei, also close to the neutron-shell closures, have been interpreted within the spherical shell model. A magic number effect is observed in ^{137}Cs with 82 neutrons:[2] While the magnetic dipole moments (for the odd-A isotopes) vary in a monotonic way from ^{133}Cs to ^{137}Cs, and all have I = 7/2, there is a reversal in sign in the hfs anomaly between the pair 133-135 and 135-137. This is a clear indication that the hfs anomaly is not simply proportional to the magnetic moment and that additional physics is reflected by it.

In the review of the experimental and theoretical status of magnetic hfs anomalies, Büttgenbach[6] points out the need for experimental data on long isotopic chains for complementary nuclear structure information as well as for developments of the hfs anomaly theory. The heavy alkali elements would constitute excellent objects for the first measurements to be made along these lines due to (i) the large hfs anomaly in the $^2S_{1/2}$ electronic ground states, (ii) the high production yields of these elements from ISOLDE, (iii) our previous experimental and theoretical experience of these elements and, maybe most important, (iv) the interesting structural variations as mentioned above. To these we add the expected relevance of the hfs anomaly measurements to the interpretation of experiments to be done in a chain of cesium isotopes[9] for the study of atomic PNC.[8]

As a preparation for the present hfs anomaly experiments, the particle-rotor model[27], previously used for the interpretation of nuclear spins and moments, has been extended to include the formalism for hfs anomaly calculations.

The initial experiments are proposed to be made on the odd-A cesium isotopes ^{121,121m,123}Cs, described by the Nilsson orbitals [422 3/2], [404 9/2] and [420 1/2], the spin I = 2 odd-odd isotope ^{126}Cs and the sequence of spin I = 1 isotopes ^{122,124,126,128,130}Cs, showing large variations in the nuclear moments.

2. THEORY

For radioactive isotopes, nuclear magnetic moments, $\mu_I = g_I I \mu_N$, are generally evaluated from measured magnetic dipole constants, a, in the hfs interaction, by a direct comparison with known values of nuclear spin I, magnetic moment and dipole constant in, e.g., a stable isotope of the same element, for which a bulk nmr experiment is possible:

$$\frac{\mu_1}{\mu_2} = \frac{a_1 \cdot I_1}{a_2 \cdot I_2} \qquad \text{or} \qquad \frac{g_1}{g_2} = \frac{a_1}{a_2} \quad . \tag{1}$$

The hfs anomaly may, however, affect significantly the results obtained from Eq. (1), and the equality in fact does not hold. Inversely, information on the hfs anomaly may be derived once experimental values are available on these quantities for a pair of isotopes.

In heavy elements with unpaired s-electrons, such as in the ground states of the alkali elements, the main contribution to the hfs anomaly arises from the distribution of nuclear magnetization over the extended nuclear volume, the so-called Bohr-Weisskopf effect.[1] It is defined by:

$$a = a_{pt}\ (1 + \epsilon), \tag{2}$$

where a is the measured hfs dipole interaction constant and a_{pt} the value corresponding to a point nucleus. For a pair of isotopes:

$$\frac{a_1}{a_2} = \frac{g_1(1 + \epsilon_1)}{g_2(1 + \epsilon_2)} \quad \text{or} \quad \frac{a_1}{a_2} \approx \frac{g_1(1 + {}^1\Delta^2)}{g_2} \tag{3}$$

where the hfs differential anomaly ${}^1\Delta^2$ for small values of ϵ equals:

$${}^1\Delta^2 = \epsilon_1 - \epsilon_2 \quad . \tag{4}$$

The formalisms for calculation of the Bohr-Weisskopf effect within different nuclear models are summarized in Ref. 6. As discussed above, there are large variations in nuclear structure along the isotopic sequences of the heavy alkali elements. The general particle-triaxial-rotor approach was shown to be quite successful in accounting for a number of the measured spins and moments.[15,23] We therefore, as a preparation to the present hfs anomaly experiments, have incorporated the formalism for calculation of the Bohr-Weisskopf effect into the particle-rotor program.

The magnetic moment and BW-effect calculations are largely analogous. The former are derived from the operator:

$$\mu = \mu_N(g_s s + g_l l + g_R R) , \tag{5}$$

where s and l denote the spin and orbital angular momenta of the odd particle and R the collective angular momentum of the core. The magnetic moment is obtained as the projection of μ on the total angular momentum I. The corresponding operator which enters in the calculations of the BW-effect is:

$$\delta\mu_{BW} = \mu_N\{ g_s\, s\, N(r) + g_s\, \tfrac{1}{2}\sqrt{10}[sxC^2]^1\, K(r) + g_l l\, [N(r) - K(r)] + g_R R\, f\} , \tag{6}$$

where r is the nuclear radius coordinate, and N(r) and K(r) integrals over the electronic wave functions.

Because of the analogy between the expressions (5) and (6), it is evident that in order to predict the BW-effect in a reliable way, the calculations of the magnetic moments should first be able to reproduce the experimental values.

By projecting the operator $\delta\mu_{BW}$ on the total spin we obtain numerical values of the BW-effect ϵ through:

$$\epsilon = -\langle\delta\mu_{BW}\rangle_I \,/\, \langle\mu\rangle_I . \tag{7}$$

With this formalism it is straightforward to carry out calculations of the BW-effect for arbitrary well-deformed or transitional nuclei. It has been applied to the neutron-deficient cesium isotopes ^{119,121,123}Cs. The results for μ and ϵ are given in Table I, with contributions from different terms separated. The values of $^1\Delta^2 = \epsilon_1 - \epsilon_2$ are of the order of 1%.

The nuclear moments of the odd-A transitional and strongly deformed cesium isotopes are well described by the Nilsson orbitals [404 9/2], [422 3/2] and [420 1/2]. A comparison between experiments and results from particle-rotor calculations, using a somewhat different parameter set, was presented at the Helsingör Conference[23] (cf. Fig. 1). At the same conference, experimental data (Fig. 2) and proposed interpretations of the nuclear moments of the spin I = 1 odd-odd cesium isotopes $^{122-130}$Cs were given. It is our expectation that the additional information from the hfs anomaly of these isotopes will help in assigning the nuclear configurations. The BW-formalism is presently being extended to cover also odd-odd nuclei, i.e. cases where one proton and one neutron couple to a deformed core.

Table I. Calculated magnetic moments μ and Bohr-Weisskopf effects ϵ within the particle-rotor model for the cesium isotopes ^{119,121,123}Cs.

	^{119}Cs I = 9/2		^{121}Cs I = 3/2		^{123}Cs I = 1/2	
	μ n.m.	ϵ%	μ n.m.	ϵ%	μ n.m.	ϵ%
$\vec{s}$	1.63	-0.252	-0.85	1.072	1.43	-0.755
$\vec{l}$	3.34	-0.328	1.39	-1.145	0.24	-0.080
$[\vec{s}\times\vec{C}^2]^1$		-0.030		0.348		-0.025
$\vec{R}$	0.34	-0.040	0.15	-0.130	-0.05	0.018
Theory	5.31	-0.65	0.69	0.14	1.63	-0.84
Exp.	5.46		0.75		1.38	

We have also[3] developed the Bohr-Weisskopf theory in the light of nuclear configuration mixing, as done for magnetic moments by Arima and Horie.[28] This allows calculations of the nuclear magnetic moments and hfs anomalies by making definite assignments of proton and neutron configurations. (A semi-phenomenological approach allows the use of moment and hfs anomaly data together to determine two principal admixtures to the odd particle wavefunction.) This should make the systematic isotopic studies of the hfs anomalies (Eq. 4) formally particularly useful for the atomic PNC work[8] as both involve the variation of the neutron configuration and orbits.

3. EXPERIMENT

The initial hfs anomaly experiments are proposed to be made on some selected cesium isotopes given in Table II. The table includes three odd-A cases with different nuclear structure: ^{123}Cs (I = 1/2) being similar to ^{125,127,129}Cs, ^{121m}Cs (I = 9/2) similar to ^{119}Cs and ^{121}Cs (I = 3/2) similar to ^{119,143,145}Cs. The spin I = 2 isotope ^{120}Cs, described by the nuclear configuration 2^+ {p[404 9/2] n[413 5/2]}, is strongly deformed, whereas the spin I = 1 isotopic sequence ^{122,124,126,128,130}Cs shows a great variation in nuclear shape and structure.

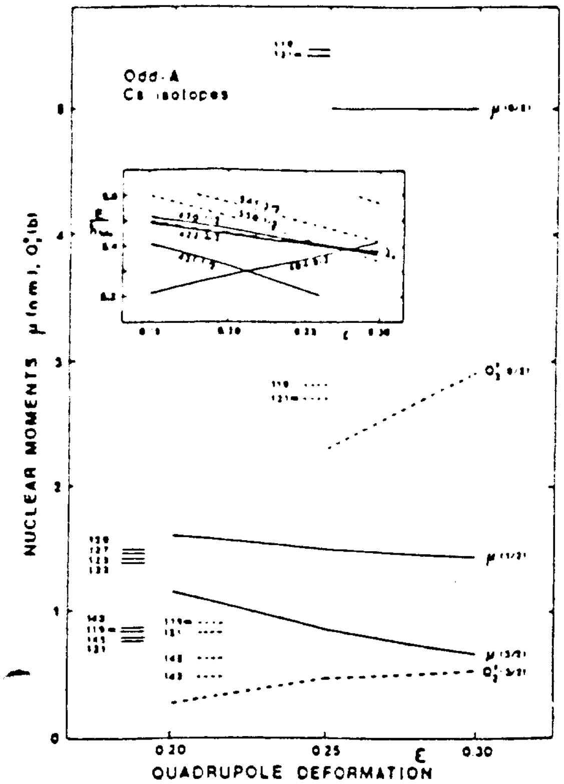


Fig. 1 Comparison between experimental and theoretical nuclear moments of the odd-A cesium isotopes $^{119-145}Cs$. The Fermi level of cesium (Z = 55) is shown in the Nilsson diagram.

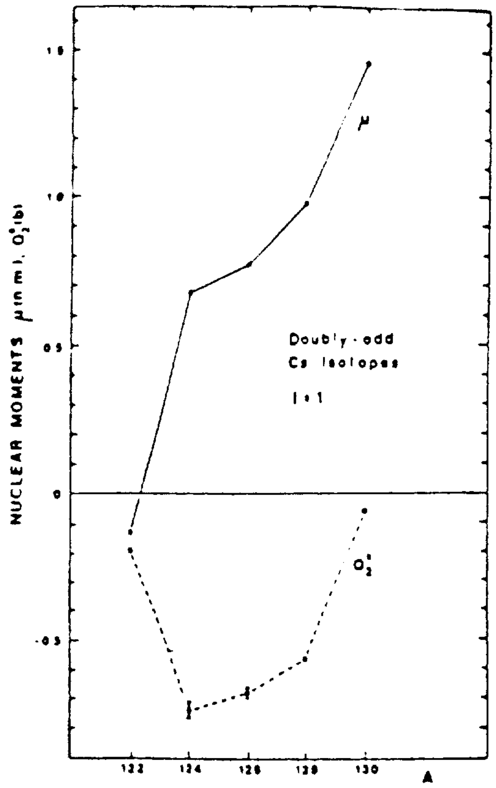


Fig. 2 Experimental nuclear moments of the spin I = 1 doubly-odd cesium isotopes $^{122-130}Cs$, reflecting the large structural variations.

Table II. Present status of hyperfine structure and nuclear properties of the cesium isotopes for which high precision data are required in the proposed hfs anomaly experiments.

A	I	$\Delta\nu$ MHz	g_I	$2g_I\mu_B B/h$ MHz at 7kG
121	3/2	3198.2(28)	0.51	5.32
121m	9/2	18725(2)	1.20	12.81
123	1/2	8578.5(37)	2/75	29.36
120	2	15083.8(60)	1.94	20.72
122	1	-619.860(3)	-0.133	1.43
124	1	3142.5(35)	0.673	7.17
126	1	3632.1(42)	0.777	8.29
128	1	4551.3(29)	0.974	10.39
130	1	6823.5(47)	1.46	15.57

Nuclear spin and hyperfine separation $\Delta\nu$ experiments have been made on these isotopes as ISOLDE.[10,11,18] The hyperfine separations, given in Table II, are related to the magnetic dipole constants through $\Delta\nu = a(I + 1/2)$. The nuclear magnetic moments or g-factors in Table II are evaluated using Eq. (1).

The hfs anomaly experiments will require high-precision data on the hyperfine separations $\Delta\nu$ as well as on the nuclear g-factors. A 10% accuracy in a 1% hfs anomaly indicates that the errors in the individual quantities should be less than 1 part in 10^5. This is easily achievable in the case of the hyperfine separations. Here, we are aiming for accuracies of the order 10^{-6}, as obtained already by rf-spectroscopy in ^{122}Cs.[10] Exceptions are the nuclides ^{121m}Cs and ^{120}Cs, having extremely large hyperfine separations. These separations have been determined, though, with a 10^{-4} accuracy by laser spectroscopy.[18]

The high-precision measurements of the nuclear g-factors will require the main effort within the project. The "field-independent doublet method" used in previous experiments on cesium isotopes close to stability[2,25,26] does not work for the low spin I = 1/2, 1 isotopes and it is inconvenient for the isotopes with large hyperfine separations, ^{120,121m}Cs. Therefore, for cases where the <u>field independent doublet method</u> is inapplicable, we have to rely on field dependent transitions. However, with the available highly homogeneous ($\sim 10^{-5}$) magnet producing the interaction field, such transitions can provide adequate accuracy. In this case we can use the so-called triple-resonance method. This is most easily explained in connection with the hyperfine structure diagram of a spin I = 1 cesium isotope shown in Fig. 3, realizing that laser light is used for polarizing the atoms and a sextupole field for the analysis. Optical pumping between the $F_2 = 3/2$ ground-state hyperfine level and the F = 5/2 level of the $^2P_{3/2}$ excited atomic state results in a population of the F = 1/2 level, i.e. a depopulation of the $m_J = 1/2$ levels, with an accompanying negative signal, since the analyzing magnets transmit only $m_J = 1/2$ atoms. By inducing at low fields the α-transition $(1/2,-1/2) \rightarrow (3/2,-1/2)$ followed by the reverse β-transition we are still at a negative signal. However, if between the two transitions, we induce at high fields the $\Delta m_I = \pm 1$ γ-transitions, resonance signals will be obtained. The frequency difference between the two γ-transitions equals the term $2g_I\mu_B B/h$, which will give a direct measure of the nuclear g-factor. Considering the magnitudes of $2g_I\mu_B B/h$, given at 7 KG external magnetic field in Table II, it is evident that resonance signals determined within a few KHz will give the desired accuracy in g_I. A successful test of the triple resonance method in an actual setup, using stable potassium, is described in the next section.

The hyperfine separations may be determined to high

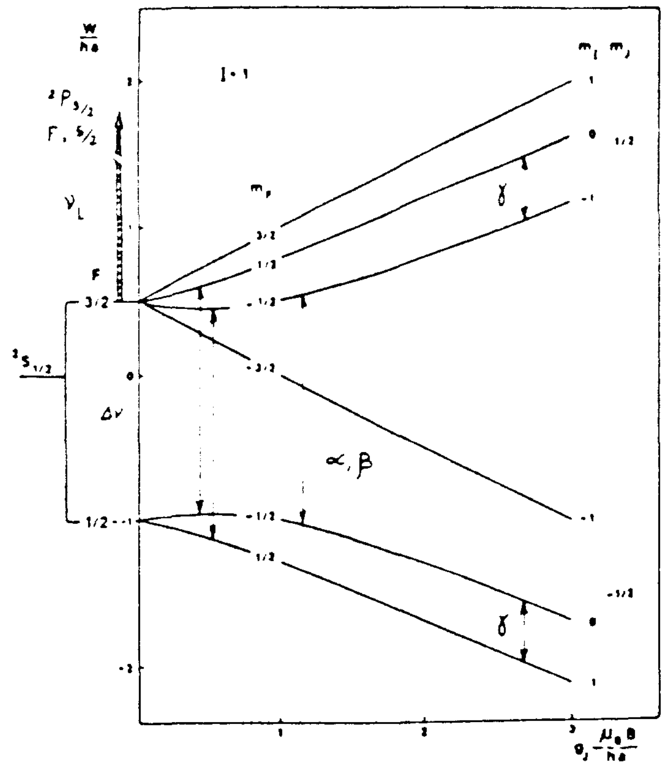


Fig. 3
Hyperfine structure diagram of a spin I = 1 cesium isotope. The transitions involved in the triple-resonance experiment for the g_I-measurement and the field independent direct transitions giving the hyperfine separation $\Delta\nu$ are indicated.

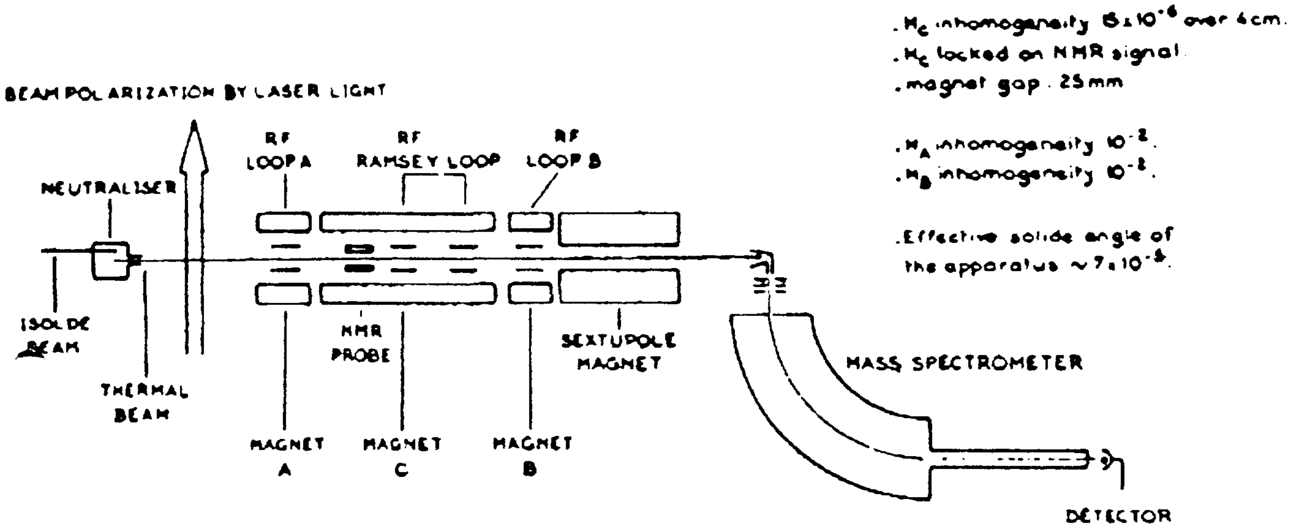


Fig. 4 Schematic view of the experimental set-up. The ion-beam from ISOLDE is converted to a thermal atomic beam on which the hfs experiments are being made. For the detection, the atomic beam is again ionized, passes a mass spectrometer and is recorded by an ion counter.

precision by inducing the "field-independent" transitions (1/2, -1/2) → (3/2, 1/2) and (1/2, 1/2) → (3/2, -1/2) at low fields, as was done in Ref. 21.

The magnetic field calibrations will be made by measuring regularly the transition (17/2, -17/2) → (17/2, - 15/2), corresponding to (3/2, -3/2) → (3/2, -1/2) in Fig. 3, of the spin I = 8 isomeric state in ^{134}Cs, for which high-precision data exist.[25] Here also enters the $^2S_{1/2}$ ground-state electronic splitting factor of cesium, which is known to high precision g_J = 2.0025410(24).[29]

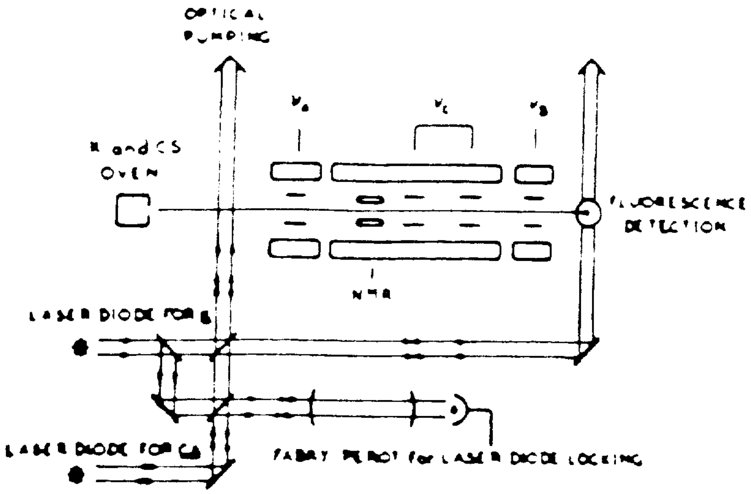
The general experimental technique will be similar to the one used by the Orsay group at ISOLDE[30] combined with the high-precision rf-technique of the Bonn group.[31] The six-pole analyzing magnet and the C magnet are provided from the Göteborg-Uppsala ABMR-apparatus.[32]

A schematic view of the experimental set-up is given in Fig. 4. The longer distance between the atomic-beam source and the entrance of the six-pole magnet in the present set-up, due to the presence of the triple-resonance system, is compensated for by the larger solid angle accepted by the new six-pole magnet, giving a transmission similar to that of the former system.[30] The production yield from ISOLDE of the cesium isotopes $^{120-130}$Cs, proposed for this study, are 2 to 4 orders of magnitude above the limit of sensitivity.

4. PROGRESS IN EXPERIMENT PREPARATION

The components of the atomic beam system have been assembled at the Laboratoire Aimé Cotton in Orsay and tested. Magnet homogeneity tests were performed. A synthesized radio frequency system for the precision rf measurements is being prepared at New York University. A test experiment to measure the nuclear g-value of stable ^{39}K was performed using the field independent doublet method and the simpler laser induced fluorescence technique in a first step: the same laser light is used to probe the atomic beam polarization after the three rf zones, by observing the induced fluorescence. In a second step, we also used the sextupole analysis. In both cases the triple resonance geometry is the same. A stabilized diode laser was used for the optical pumping and fluorescence detection. (For cesium, room temperature laser diodes are now also readily available for the optical pumping and fluorescence detection.) A schematic of the experiment is shown in Figs. 5 and 6.

In the laser induced fluorescence experiment (Figs. 5,6), the laser frequency was tuned to the transition ($^2S_{1/2}$, F=2) ↔ ($^2P_{3/2}$) and the fluorescence light is detected after the three zones A, B, C. If the pumping light is now switched on, the atoms are transferred from the ($^2S_{1/2}$, F=2) to the ($^2S_{1/2}$, F=1)



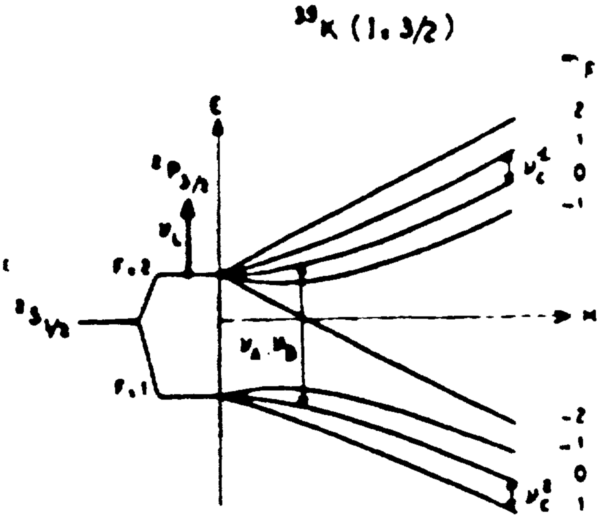


Fig. 5

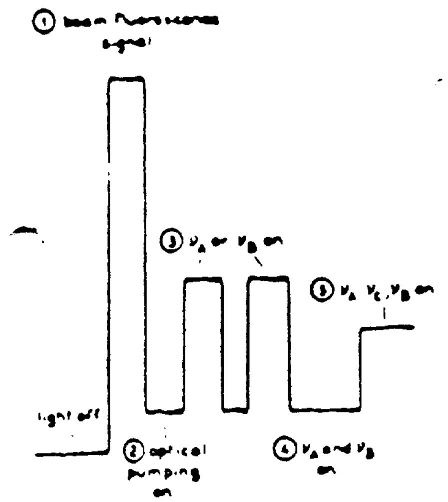


Fig. 6

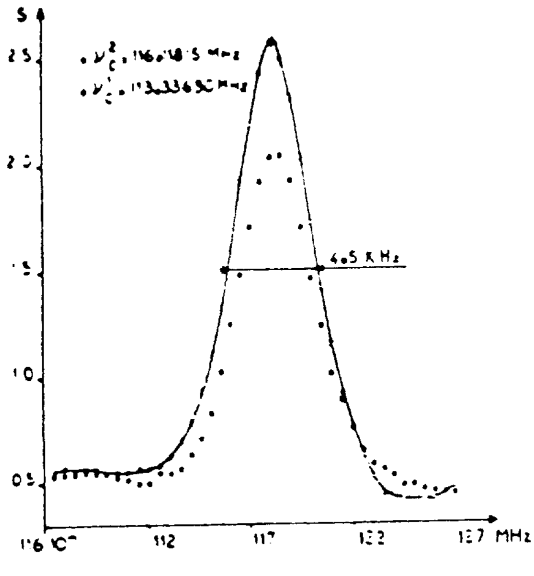


Fig. 7

level and the detected fluorescence is strongly decreased. By inducing, at low field (25 G), the magnetic transition ($F=1$, $m_F=0$) $\leftrightarrow$ ($F=2$, $m_F=0$) in zones A or B, the level $F=2$ is repopulated and the detected fluorescence increased. Next, with both rf frequencies on resonance in A and B, the atoms first transferred to ($F=2$, $m_F=0$) at A will be brought back to ($F=1$, $m_F=0$) at B and the detected fluorescence vanishes. If now, in addition, the rf resonance ν_1($F=2$, $m_F=0 \leftrightarrow F=2$, $m_F=1$) at high field (about 7000 G) is on, the atom in ($F=2$, $m_F=0$) after zone A will be transferred to ($F=2$, $m_F=1$) after zone C, and then, being out of resonance at B, it remains in ($F=2$, $m_F=1$), and consequently the fluorescence signal increases. A similar process is repeated for the high field transition ν_2($F=1$, $m_F=0 \leftrightarrow F=1$, $m_F=1$).

From the Breit-Rabi Hamiltonian we find readily:

$$\nu_1 - \nu_2 = 2g_I\mu B \quad . \tag{8}$$

B is locked to a NMR probe signal and is measured by rf resonance on an atomic cesium beam from the same oven. The rf frequency corresponds to the highly field dependent transition ($F=3$, $m_F=-3 \leftrightarrow F=4$, $m_F=-4$). The accuracy obtained is better than 1 part in 10^6.

To get narrower lines, Ramsey loops are used in the C field which is homogeneous to the order of 10^{-5} over a volume of 4 cm^3. The FWHM line widths obtained range from 3.8 to 5 kHz depending on the strength of the rf field used. The rf resonances for the doublet frequencies are shown in Fig. 7. The result for the nuclear g factor obtained is in excellent agreement with the published value, and confirms the performance of the system. Most of the error is due to the determination of the central frequency. In the ^{39}K experiment, $2g_I\mu B$ = 2.78 MHz at 7000 G and the error is about 45 Hz (or 1% of the line width).

On line, the conditions are of course different, in particular the number of particles is much less than in a beam of stable isotopes. It has been shown in an on line ABMR experiment with a similar setup[21], using 10^6/s ^{76}Rb particles, that an uncertainty of 4 kHz is observed with a much broader resonance (50kHz). For the cesium isotopes, in which we are interested, the production rate expected is more than 10^9/s. The effect to be observed is much larger than in potassium, $2g_I\mu B \approx 10$ MHz at 7000 G. A precision of 10^{-4} would require an error of less than 1 kHz with a line width of 5 kHz, which seems quite reasonable from the ^{76}Rb case.

5. PLANNING FOR THE EXPERIMENTS

Following the acceptance of the experiment, we expect to move the ABMR apparatus to CERN as soon as the PSB ISOLDE facility permits. At the Leysin Workshop, ISOLDE plans gave an estimate of this to be early 1993.

The apparatus will require a floor space of 2.5 m x 5 m.

The experiments will be made on radioactive isotopes of cesium for which the target and ion-source techniques are well established at ISOLDE.

Following a test period of 4 shifts, the experiments on the nine cesium isotopes in Table II will require 4 shifts each, with 1 shift for the measurement of the dipole constant and 3 shifts for the g-factor, adding up to a total of 40 shifts, requested for a period of two years.

A successful completion of these experiments will be followed by a request for further hfs anomaly measurements in the heavy alkali elements as discussed above.

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